Extensive population synthesis of isolated neutron stars with field decay

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Abstract. We perform population synthesis studies of different types of neutron stars (thermally emitting isolated neutron stars, normal radio pulsars, magnetars) taking into account the magnetic field decay and using results from the most recent advances in neutron star cooling theory. For the first time, we confront our results with observations using *simultaneously* the Log N – Log S distribution for nearby isolated neutron stars, the Log N – Log L distribution for magnetars, and the distribution of radio pulsars in the $P-\dot{P}$ diagram. For this purpose, we fix a baseline neutron star model (all microphysics input), and other relevant parameters to standard values (velocity distribution, mass spectrum, etc.), only allowing to vary the initial magnetic field strength. We find that our theoretical model is consistent with all sets of data if the initial magnetic field distribution function follows a log-normal law with $<\log(B_0/[G])>\sim 13.25$ and $\sigma_{\log B_0}\sim 0.6$. The typical scenario includes about 10% of neutron stars born as magnetars, significant magnetic field decay during the first million years of a NS life (only about a factor of 2 for low field neutron stars but more than an order of magnitude for magnetars), and a mass distribution function dominated by low mass objects. This model explains satisfactorily all known populations. Evolutionary links between different subclasses may exist, although robust conclusions are not yet possible.

We apply the obtained field distribution and the model of decay to study long-term evolution of neuton stars till the stage of accretion from the interstellar medium. It is shown that though the subsonic propeller stage can be relatively long, initially highly magnetized neutron stars ($B_0 >\sim 10^{13}$ G) reach the accretion regime within the Galactic lifetime if their kick velocities are not too large. The fact that in previous studies made >10 years ago, such objects were not considered results in a slight increase of the Accretor fraction in comparison with earlier conclusions. Most of the neutron stars similar to the Magnificent seven are expected to become accreting from the interstellar medium after few billion years of their evolution. They are the main predecestors of accreting isolated neutron stars.

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INTRODUCTION

Young neutron stars (NSs) appear as sources of different visible nature: radio pulsars (PSR), soft gamma-ray repeators (SGRs), anomalous X-ray pulsars (AXPs), rotating radio transients (RRATs), central compact objects in supernova remnants (CCOs), cooling close-by NSs dubbed the Magnificent seven (M7). Some NSs show several types of activities. Step by step we realize that in many cases we cannot speak about different subpopulations with different evolutionary paths: sources evolve from one type to another. One way to explain it is to consider the magnetic field evolution.

On one hand, it is known that at least the activity of magnetars (SGRs and AXPs)

is due to the release of their magnetic field energy. On another hand, for most of other types of NSs there is no direct evidence in favour of significant role of the magnetic field decay. This controversial situation is explained in the scenario studied by Pons et al. (see, for example, [1] and references therein). In this contribution we briefly summarize the results published in [2, 3], which are based on this scenario of field evolution. We perform population synthesis of several subpopulations of isolated NSs to derive a universal initial magnetic field distribution, and to study the destiny of old NSs in this scenario.

THE MODELS

Here we follow the paper [2]. We use three models to perform population synthesis of close-by cooling NSs observed by ROSAT, population synthesis of galactic magnetars, and, finally, population synthesis of isolated normal PSRs.

Close-by cooling NSs

Here our calculations are based on the model described, for example, in [4] and references therein. NSs of different masses (we use eight values from 1.1 to 1.76 $M_{\odot}$) and different initian magnetic fields (we use seven values from $3\,10^{12}$ G to $3\,10^{15}$ G) are evolved in the solar vicinity (initial distance $<$ 3 kpc) till they are detectable by ROSAT above $\sim$ 0.01 cts/s from several tens of pc. Interstellar absorption is taken into account. Results are calculated for the ROSAT PSCP and confronted with observations. For normalization it is assumed that 270 NSs are born inside 3 kpc from the Sun in a Myr. The Gould belt contribution is taken into account. Outside the Belt NSs are mainly born in known large OB associations.

Interested readers can look at the on-line version of the population synthesis of isolated close-by cooling NSs: http://www.astro.uni-jena.de/Net-PSICoNS/ (Boldin, Popov, Tetzlaff, in press).

Magnetars

We made a simple model to calculate Log N – Log L distribution for galactic magnetars which is confronted with the data on known sources of this kind, and with limits derived by [5]. As we calculate distribution in luminosity, not in flux, we do not take into account interstellar absorption.

To calculate luminosities we apply the same cooling curves with additional heating due to magnetic field decay which are used for the population synthesis of close-by isolated NSs. The same mass spectrum was applied. As before we consider that the initial magnetic fields are uncorrelated with masses.

In this modeling no Monte Carlo simulation is done. Instead, we use complete cooling tracks of NSs with different masses and magnetic fields to estimate the whole Galactic population of NSs with a given luminosity. Absolute numbers are obtained by normal-

ization to the total birth rate of NSs. We use the Galactic NS formation rate equal to 1/30 yrs^{-1}.

Radio pulsars

We have performed Monte Carlo simulations to generate a synthetic PSR population and confront our models with observations. The methodology employed in the simulations closely follows the work by [6] but some parameters of their model are allowed to change according to the results of our previous calculations. The main goal of this modeling is to answer the following question: can we obtain a synthetic PSR population compatible with the observed one and consistent with our previous description for magnetars and close-by isolated NSs? To this end, we start from the optimal population model parameters obtained by Faucher-Giguère and Kaspi [6] and modify only the initial period and magnetic field distributions to account for the effect of magnetic field decay consistent with our model.

To generate the PSR synthetic population we first choose the parameters of the NS at birth closely following the model described by [6], which we briefly summarize. The place of birth is obtained according to the distribution of their progenitors (massive Population I stars) which are mainly populating the Galactic disk and more precisely its arms. The velocity at birth is distributed according the exponential distribution with a mean value of 380 km s^{-1}.

The spin period of the star at birth, P_0, is chosen from a normal distribution with a mean value of $< P_0 >$ and standard deviation σ_{P_0}. Of course, only positive values are allowed. The initial magnetic field at the magnetic pole is obtained from a log-normal distribution with mean value $< \log(B_0/[\mathrm{G}]) >$ and standard deviation $\sigma_{\log B_0}$.

Once we have chosen the properties of the NS at birth we solve the appropriate differential equations to obtain the position, period and magnetic field at the present time. We use a smooth model for the Galactic gravitational potential. The period evolution is obtained by assuming that the rotation energy losses are due to magnetic dipolar emission (orthogonal rotators), where the magnetic field is obtained from our magneto-thermal evolutionary models.

At the end of the Monte Carlo simulation we end up with a synthetic population of PSRs to be compared with a given observed sample. We use the PSRs detected in the Parkes Multibeam Survey (PMBS) sample [7] and, to limit the contamination of our sample by recycled PSRs, we further ignore the PSRs with $P < 30$ ms or $\dot{P} < 0$, and those in binary systems. With this restrictions, our resulting sample contains 977 objects. We use the parameters for detectability in the survey, radio luminosity and beaming given in [6].

RESULTS OF POPULATION SYNTHESIS FOR YOUNG NEUTRON STARS

Our main result is the following: we are able to explain three different populations of isolated NSs (close-by cooling NSs, magnetars, PSRs) using the same set of ini-

tial distributions in the framework of decaying magnetic field. We derived "the best" model for the initial magnetic field distribution: it is the log-gaussian distribution with $< \log(B_0/[\mathrm{G}]) >\sim 13.25$ and $\sigma_{\log B_0} \sim 0.6$. Of course, real distribution can be more complicated, but we can put a constraint on the fraction of magnetars. Our results show that it should be below 20%, most probably $\sim 10\%$.

OLD NEUTRON STARS

We use "the best model" for the initial magnetic field distribution to study the destiny of old isolated NSs in the Galaxy. We perform a population synthesis similar to [8], but with significant upgrade both in the model and in the parameters.

We show that due to a significant fraction of highly magnetized NSs (which was neglected in earlier studies) many objects can reach the stage of accretion from the interstellar medium. In the solar vicinity about 40% of isolated NSs can be accreting.

CONCLUSIONS

Here we presented some results which can be considered as one of the first steps towards the "grand unification in neutron stars" [9]. We described several types of isolated NSs in the framework of decaying magnetic field using the same initial distributions. In addition, we demonstrated that due to relatively large fraction of initially highly magnetized NSs, many old objects can start to accrete from the interstellar medium.

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